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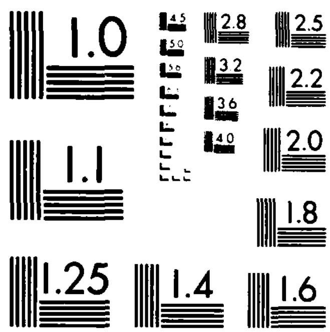

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ROYAL AIRCRAFT ESTABLISHMENT

ON-BOARD PROCESSING FOR LINESCAN SENSORS IN MINIATURE UNMANNED AIRCRAFT

by

J. A. C. Beattie

January 1984

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Procurement Executive, Ministry of Defence
Farnborough, Hants

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LIST OF CONTENTS

1 INTRODUCTION

This Memorandum discusses forms of image processing of linescan data, that might profitably be performed on-board a small unmanned air vehicle.

The aim of the image processing is to reduce the data bandwidth for transmission over a radio frequency link to the ground display station, to improve the quality of the transmitted image, and to simplify the extraction of intelligence from the image. The bandwidth reduction and information extraction may be enhanced or supplemented by on-board processing to prefilter the data for target detection and target motion detection. Full use of automatic target detection can only be made in conjunction with a navigation system to give ground coordinates for the target data. Alternatively, navigation and air vehicle attitude data can be obtained from the on-board linescan image processor, given the appropriate sensor and processing algorithms (see section 7).

The sections below identify the characteristics of linescan imagery and show, for those suitable for on-board processing in the air vehicle, the parameters and limits of operation.

2 SYSTEM DESCRIPTION AND CONSTRAINTS

A video processing payload for a slow scan imager is postulated and shown in the block diagram of Fig 1 (see also Ref 1). Throughout this Memorandum, the assumed sensor is a miniature infrared linescan, the design parameters of which are listed in Appendix A. The linescan sensor gives a static image of the ground scene overflown, built up line by line. Each line is swept out through the rotation of a mirror on to a 'point detector'. Such a system can have a wide field of view, high resolution and a bandwidth significantly less than that required for CCIR television compatible sensors but with a higher data content in the instantaneous swathe of imagery.

The received image is not in 'real time', in that the displayed scene is sensed non-redundantly at a rate which is related to the air vehicle's ground speed. This means that target motion cannot be observed, although target motion intelligence is present in the image. Also the control of detector off-set and gain cannot be used in real time to enhance particular features of the displayed image, but general thermal conditions can be compensated at the sensor automatically or remotely. Normal contrast and brightness controls would be available for variations in viewing conditions at the ground station.

The scan conversion of the slow scan data to CCIR television format, suitable for display on a standard monitor, is dependent on the air vehicle parameter V/h, that is the ratio of the air vehicle's ground speed to its height above ground, in units of radians per second. The range of values of V/h assumed in this Memorandum is 0.3 to 0.01 rad/s, corresponding to an unmanned aircraft with speeds between 20 and 100 m/s and heights from 300 to 2000 m.

3 ANALOGUE TO DIGITAL CONVERSION

3.1 Anti-aliasing filter

A filter is required to prevent the aliasing of high frequency electrical noise into the passband of the video system due to the limited sampling rate of the analogue

to digital converter (ADC). It is most likely to be an analogue filter placed at the input to the ADC. Alternatively, integrating over the pixel time-window prior to sample and hold would achieve the same effect.

3.2 Digitisation data rates

The pixel rate, and hence the ADC sampling rate, is a function of the detector subtense, the sensor field of view, the scan efficiency, and the scan rate. The scan efficiency is the ratio of the line time to active video time, and for the assumed sensor is 75%. The pixel rate for the assumed sensor is 2.24 Mpixel/s for unit aspect ratio detector footprint at the nadir.

The rate of digitisation is defined by the pixel data rate given above. The burst length for the ADC is given by the geometric relationship between the field of view of the sensor and the subtense of the detector. For the assumed sensor the line consists of a maximum of 4189 pixels, but a lower number of pixels may be acceptable, see sections 5.4 and 7.1.

4 VIDEO DYNAMIC RANGE

4.1 System constraints

The number of bits required to describe each pixel depends on the dynamic range of the scene being viewed, and is limited by the dynamic range of the detector. It is constrained in use by the bandwidth of the radio link to the ground station, and the bandwidth of the display. For a CCIR television system, an 8 bit pixel gives a good picture with 48 dB signal to noise ratio. A 6 bit pixel gives an acceptable picture with 32 dB signal to noise ratio, and provides a lower limiting value. However the dynamic range of the video from the assumed sensor is given by the scene temperature range and the detector sensitivity. Assuming a scene range of 263 K to 423 K (*ie* -10 to +50°C) the dynamic range is 64 dB which requires 11 bits/pixel. This could be reduced in a real time sensor when the off-set and gain may be optimised for the area of interest, but only adjustment for the general thermal conditions is possible with a linescan sensor. The dynamic range is increased when hot targets are taken into consideration, that may be over 100°C.

4.2 Reduction of dynamic range

The nature of the thermal emissions from the observed scene are such that there is a low spatial frequency variation of wide dynamic range, superimposed on which is a high spatial frequency component of low dynamic range. More significant intelligence reside in the latter. Extraction of intelligence from the data is facilitated by selectively compressing the low spatial frequency component, and amplifying the high frequency component, to fully use the dynamic range of the transmission channel and the display. The change-over frequency must be found by experiment with typical data.

5 CORRECTION OF IMAGE DISTORTION

5.1 Velocity-to-height compensation

On all occasions except when operating at the limiting V/h , the sensor will be overscanning the scene and the data rate will be higher than necessary by an amount proportional to the amount of overscan. Since each line will be placed on an adjacent line on the display by the scan converter, the image will appear stretched in the along track direction. If the overscanned lines are integrated together to give contiguous lines, the image aspect ratio will be corrected on the display with the additional benefit of an improvement of video signal to noise ratio. It will also be possible to reduce the data rate by using the integration time to output one contiguous line. However, integration will also reduce the along track resolution by increasing the effective sampling aperture in the flight direction, and a compromise must be made. It is clearly important not to employ a scan rate higher than that needed for the maximum combined V/h and pitch rate to be encountered (see section 5.2 below).

The amount of overscan is a function of the line time, the detector subtense and V/h , and for the assumed sensor will be in the range 1 to 30 lines.

The weighting function used for the integration will be a compromise between improving the signal to noise ratio of the video, increasing the sampling aperture along the track, and introducing motion blurr into the image. The two preferred weighting functions are square, or equal weighting, to maximise signal to noise ratio, and a sawtooth function to minimise the resolution loss and the introduction of motion blurr. If other more complex weighting functions are used, such as running average or a triangular weighting function, then line storage is required up to $n-1$ lines, where n is the number of lines being integrated.

5.2 Pitch motion compensation

If a significant number of lines are required to be integrated together. then it is possible to compensate for air vehicle pitch motion by modifying the number of lines being integrated by a function proportional to the secant of the pitch angle and the rate of change of pitch angle. That is, adjusting integration to match the apparent V/h . Since the pitch angle for which compensation might be made will be small, the secant term may be ignored.

5.3 Yaw correction

Yaw correction is best performed during scan conversion, when the received line can be placed in the digital scan converter store in the correct orientation to remove the yaw distortion, and smoothing performed to remove the stepped edge of non-orthogonal digital lines. The angle of yaw can be obtained from the air vehicle flight control system, or the correlation process described below. Data from lines of varying orientation that overlap may either be averaged or ignored.

5.4 Roll compensation

If the sensor is not stabilised against air vehicle roll, distortion of the image proportional to the angle of roll will result, giving a curved appearance to straight

line objects parallel to the flight path. Ideally, each picture element would have associated a roll corrected synchronisation pulse allowing perfect reconstruction of the image.

However, if some field of view is sacrificed, then satisfactory roll compensation can be achieved by delaying the start of the digitisation of the video by a time proportional to the roll angle. Since compensation will be required in both directions of roll about the nadir, a reduction in the line length required to be digitised is made. For the assumed sensor, if roll compensation is made over +30 to -30 degrees the useful line length reduces to 2793 pixels, giving a 120 degree field of view.

In Ref 2 M. Glover describes work done at RAE to design an analogue system for coding roll information onto a composite linescan signal.

5.5 Rectilinearisation

Linescan systems are not rectilinear. Due to the use of equal angle sampling rather than equal ground 'footprint' sampling, there is a change in size and apparent linear scan velocity, of the projected detector footprint with scan angle.

Due to equal angle sampling, as the scan angle, and hence the slant range increases, the 'footprint' (given by the product of the detector subtense and height above ground) is increased by $\sec\theta^2$ in the across-track direction, and by $\sec\theta$ in the along track direction, where θ is the scan angle from the nadir.

This gives the swath a 'bow tie' shape, where line overscan occurs at the extremities of sweep angle, for lines that are contiguous at the nadir.

5.5.1 Along track compensation

The effect of the distortion on the scan converted image is a compression of the image along track as the scan angle increases, due to the decrease in effective V/h with scan angle and the increase in scan velocity at the ground, proportional to $\sec\theta^2$ across track. Compensation requires, for lines that are contiguous at the nadir, that pixels occupy $\sec\theta$ display lines as sweep angle θ increases. This might be achieved by increasing line integration with scan angle. For small displayed fields of view, the error can be minimised by integrating lines to give a correct display either side of the nadir, say at -25 and +25 degrees.

5.5.2 Across track compensation

Similarly, to give uniformity of pixel size along the line, pixels will require integration, such that the number integrated is given by the ratio $\left(\sec(\theta_{max})^2\right)/(\sec\theta^2)$ pixels, where θ_{max} is the maximum scan angle required to be displayed.

However, since this will cause a loss of resolution at the nadir, of magnitude depending on the maximum scan angle chosen, it may be considered inappropriate to perform this compensation simultaneously over the whole image, except for navigational uses. Compensation of selected sections of imagery may be applied with greater precision in the ground-based scan converter.

6 DATA COMPRESSION

There are a number of ways in which the image data can be coded to further reduce the amount of data to be transmitted and hence reduce the required bandwidth of the transmission channel or increase its resistance to external interference.

Work done at RSRE[3] on framing sensor systems shows that good results can be obtained using the Walsh-Haddamard transform, coded using differential pulse code modulation. However, since linescan is an inherently simpler system than television, a simpler coding may be more applicable. Codes based on differencing or run length may well be adequate.

7 DUAL SENSOR SYSTEMS

7.1 Sensor system

A second detector in a linescan sensor system allows significantly more information to be obtained, at little increase in bandwidth compared with a television system. The assumed sensor has two detectors looking forward and aft of the nadir through common optics. Correlation of the signals will give a measure of the air vehicle's motion, determined by the time taken for the rearward looking detector to detect the same object that the forward looking detector has passed. Thus height or velocity of the air vehicle can be calculated if the other is known. For the assumed sensor, the time delay for correlation will be 6.3h/V ms.

Since the field of view is a forward look from a downward looking linescan, and not a forward pointing linescan, the projected swath will not be linear, but will in fact curve as scan angle increases, giving a parabolic scan pattern on the ground. Thus for correlation, only the centre portion of the line is usable when the deviation from the desired swath is no more than 1 pixel. The assumed sensor permits correlation over a field of view of -28 to +28 degrees resulting in a line length of 1314 pixels.

For the assumed sensor, the signal output from the two detectors is multiplexed line by line, with each line identified with its detector.

7.2 Line correlation

For continuous correlation, the line storage requirement is a function of the toe-in of the two detectors, and for the assumed sensor is nine contiguous lines.

The storage requirement can be reduced to one line if the correlation algorithm is initiated only on the completion of the previous correlation attempt (or a 'time out' if the correlation was unsuccessful). The time between correlations for the assumed sensor in this mode will be between 21 and 630 ms, which is compatible with any navigational system that might employ the correlation data.

The yaw vector of the air vehicle can also be extracted from correlation data by correlating across track as well as from line to line, provided that roll corrected data is used.

7.3 Correlation algorithms

The simplest algorithm is image subtraction. The scene variation during the correlation time will be negligible, and the matching of the detector preamplifier performance

should provide no problems. Correlation speed may be increased by preprocessing the video to 1 bit per pixel. However, since the correlation is between two fairly short linear arrays it may be more efficient to use a more complex correlation algorithm without preprocessing the data.

Due to the random nature of the data, algorithms can only be developed by trial with data of representative scene content and intensity modulations (see Appendix C).

The same techniques may be applied between the received image and a digital reference 'map' stored on board, for scene matching navigation.

7.4 Moving target indication

Correlation will also indicate if there has been any movement of targets in the time between the two views. If only pairs of single lines are correlated, then the relative motion vector is restricted to being across track. However, if extra storage is provided, target motion in any direction relative to the air vehicle could be identified (see Fig 2).

The line storage required will depend on the relative motion of the target and air vehicle, and in the limiting case of equal velocities the storage required is infinite. This can be reduced to a figure of say 84 lines, if the maximum target speed is 60 mph and the air vehicle has at least a 10% advantage.

8 SIGNAL FORMATS

8.1 Serial analogue video

For transmission down an analogue radio link, analogue video is required. A 1 volt peak signal into 75 ohms simplifies the interfacing since it complies with standards widely adopted. To minimise the bandwidth required, a line buffer will allow the data to be output at the slowest rate possible, depending on the line integration time.

Synchronisation must be maintained to facilitate the digitisation of the signal at the ground station for scan conversion to television display. A composite synchronisation pulse included in the signal, having a fixed time relation with the start of video, and modified by the roll compensation requirement, gives acceptable results at the V/h ratios assumed.

8.2 Serial digital video

The line buffer referred to above will also facilitate parallel to serial conversion, and minimise the bandwidth of a digital bit stream. The simplest coding is an NRZ format data stream, but reconstitution of the clock signal at the ground station is a non-trivial matter. Systems such as Manchester code simplify clock detection but with a doubling of the bandwidth. If a 6 bit pixel is accpetable, using 2 bits of an 8 bit byte for synchronisation provides for simple detection of the clock signal, and maintains a standard byte structure with only a 33% time penalty. Any other pixel word size could be used to minimise the bandwidth, but this will require word packing circuitry and will have to be decoded at the ground station.

8.3 Extracted image features

Formatting extracted image data, such as target detection, for interfacing to the radio frequency link will require the establishment of data codes for target type and location.

9 COMPUTING POWER AND MEMORY CAPACITY REQUIREMENT

The speed requirement is set by the data input rate, and for the assumed sensor will require a cycle time of 50 ns.

The storage capacity required is of the order of 66 kbits for line integration and output, and 500 kbits for correlation and moving target indication. This latter figure could be reduced by reducing the breadth of the operational requirement, for example limiting the maximum detectable target speed.

Techniques such as parallel pipe line processing and distributed array processing (with local memory), may well find application for all of the image processing described above, and particularly where storage is required, but at present are not available in a form suitable for use in miniature unmanned air vehicles.

10 CONCLUSION

This Memorandum has set out the areas of interest in image processing that might be performed on data from an infrared linescan sensor. The sensor being designed for use on miniature unmanned aircraft imposes limits of cost, power, size and weight on any flight equipment.

Appendix A

MINIATURE INFRARED LINESCAN SENSOR

The miniature infrared linescan sensor consists of an eight element Mullard Sprite detector, using the centre element or the first and eighth elements, viewing the ground through a reflective optics system employing a three faceted mirror rotating at 8000.

Basic data is tabulated below:

Field of view	±90°
Detector subtense	0.75 mrad
Stereo toe in of outer pair of elements	6.3 mrad
Line time	2.5 ms
Scan efficiency	75%
Range of velocity	25 100 m/s
Range of height	300 m
V/h maximum	0.[illegible] rad s^{-1}
System NET	0.15 K
Pixel time	446 ns

Appendix B

LINESCAN FORMULAE

SYMBOL LIST

e	Video efficiency
A	Field of view
r	Detector subtense
V	Air vehicle ground speed
h	Air vehicle height above ground
f	Number of facets to scan mirror
t_l	Line time
ψ	Pitch angle
p	Pitch compensation
I	Number of lines integrated
θ	Scan angle
β	Toe in angle of the two outer detector stripes
n	The number of pixels per line
U	The ground speed of the target

Line time $\quad t_l = \dfrac{60}{f \times s}$ seconds

Scan efficiency $\quad e = \dfrac{A/2}{2\pi/f} \times 100\%$

Active line time $\quad ta = t_L e$ seconds

Pixels per line $\quad n = \dfrac{A}{r}$ pixels

Pixel time $\quad tp = \dfrac{ta}{n}$ seconds

Swath width $\quad \omega = 2h \tan\theta$ metres

'Footprint' $\quad l_{at}$ by l_{ct} = $hr \sec^2\theta$ by $hr \sec\theta$

V/h max $\quad = \dfrac{r}{t_L}$ radians per second

Line integration $\quad = \dfrac{rh}{t_L V}$ lines

Pitch compensation (effective variation in velocity due to pitch motion) $\quad V_c = V \pm \dfrac{d\psi}{dt} h \sec\psi$ metres per second

Roll compensation $\quad = \dfrac{A}{ta}$ degrees per second

Across track integration $= \dfrac{\sec^2\theta_{max}}{\sec^2\theta}$

Stereo correlation delay $= \dfrac{2\tan\phi}{r}$ lines

Forward look line curvature $= \dfrac{2\tan\phi}{r}(1 - \cos\theta)$ pixels from linear

Area rate of presentation $= 2\,hV\tan\theta$ square metres per second

Time for one TV frame $= \dfrac{n}{512}\dfrac{rh}{V}$ seconds

Appendix C

RAE PRELIMINARY SIMULATION STUDIES USING A MICRO CONSULTANTS PLC, INTELLECT 1

C.1 Introduction

The Micro Consultants Intellect 1 is a digital frame store of 512 × 512 pixels of 8 bits per pixel. The digitising interface is capable of digitising 512 pixels to 8 bits at a maximum rate of 510 kHz, and feeds directly into the frame store via a direct memory access (DMA) port.

The controlling computer is a Computer Automation 'Alpha LSI 2' operating under the Micro Consultants disc operating system MOSS 11, which produces RT 11 equivalent floppy discs. The frame store is controlled via a high level language written by Microconsultants called ART. This has a BASIC like structure but with limited 16 bit integer arithmetic. Thus summations are limited to maximum values of 32767.

C.2 Integration

Data from the miniature infrared linescan was read in at the maximum rate (giving a resolution loss of 4:1) with a suitable sync. pulse delay to give a 90^{o} field of view centred on the nadir. No line skip was used and the image appeared stretched in the along track direction. Integration was performed with two, three and four lines and various weighting functions. However, since this produces a result in a quarter of a picture or less, it is insufficient to make any sensible deductions.

It was clear however, that the square or equal weighting function gave a clean crisp image, particularly if there was any repetitive minor line jitter. The sawtooth weighting function gave an acceptable picture but the line jitter noise was much more intrusive.

The weighting functions tried are shown in Fig 3.

C.3 Correlation

Attempts at correlation were made with data from another sensor built for Space Department, RAE, employing two Fairchild optically sensitive CCD linear arrays, of 1024 elements on a 13 microns pitch, behind a 10.2 mm focal length lens. The two sensors make an angle of 7.5^{o} to the nadir, giving a stereo delay of 230 lines. The sensor is operated in such a way as to maximise the optical integration time, so all lines are contiguous with no integration required. The sensor is gimbal mounted and is stabilised in roll with signals from a vertical gyro. The sightline is stablised in pitch by a mirror mechanically coupled to the same gyro. No yaw stabilisation is provided.

The digitising interface to the Intellect provides for the full field of view of $\pm 30^{o}$ with a reduction of resolution of 2:1. The video lines are multiplexed alternately from forward and rearward looking arrays, and the frame store separates the two images into the two fields of the television display.

Justifying the two images showed that there was yaw distortion but that for the images chosen the centre portion was sufficiently similar to encourage correlation attempts.

An estimate of the stereo line delay was made, and the Intellect programmed to attempt a correlation for ten lines either side of the estimate. Correlation was also looked for along the line for up to 10 pixels either side of the vertical.

Two correlation algorithms were tried, a simple subtraction and a standard normalising correlation function as given in Fig 3.

Both functions seemed to be image content dependent, and both showed a tendency to give a correlation distance that showed a sawtooth dependence with distance down the picture. The work suffered from having to make simplifying assumptions and numerous divisions in order to keep summations within the maximum integer size.

C.4 Future work

SNC3 has now replaced the CA Alpha LSI 2 with a more powerful CA Alpha LSI 4. This latter has Fortran capability and the above experiments will be repeated using Fortran routines.

REFERENCES

No	Author	Title, etc
1	P. Gardner	Imaging sensors for small unmanned aircraft. RAE Technical Memorandum Space 321 (1983)
2	M. Glover	Electronic roll compensation for linescan imagers. RAE Technical Memorandum Space 328 (1984)
3	B. Derby	Bandwidth compression and spread spectrum protection of video links against jamming. RSRE Memorandum 3088, August 1977

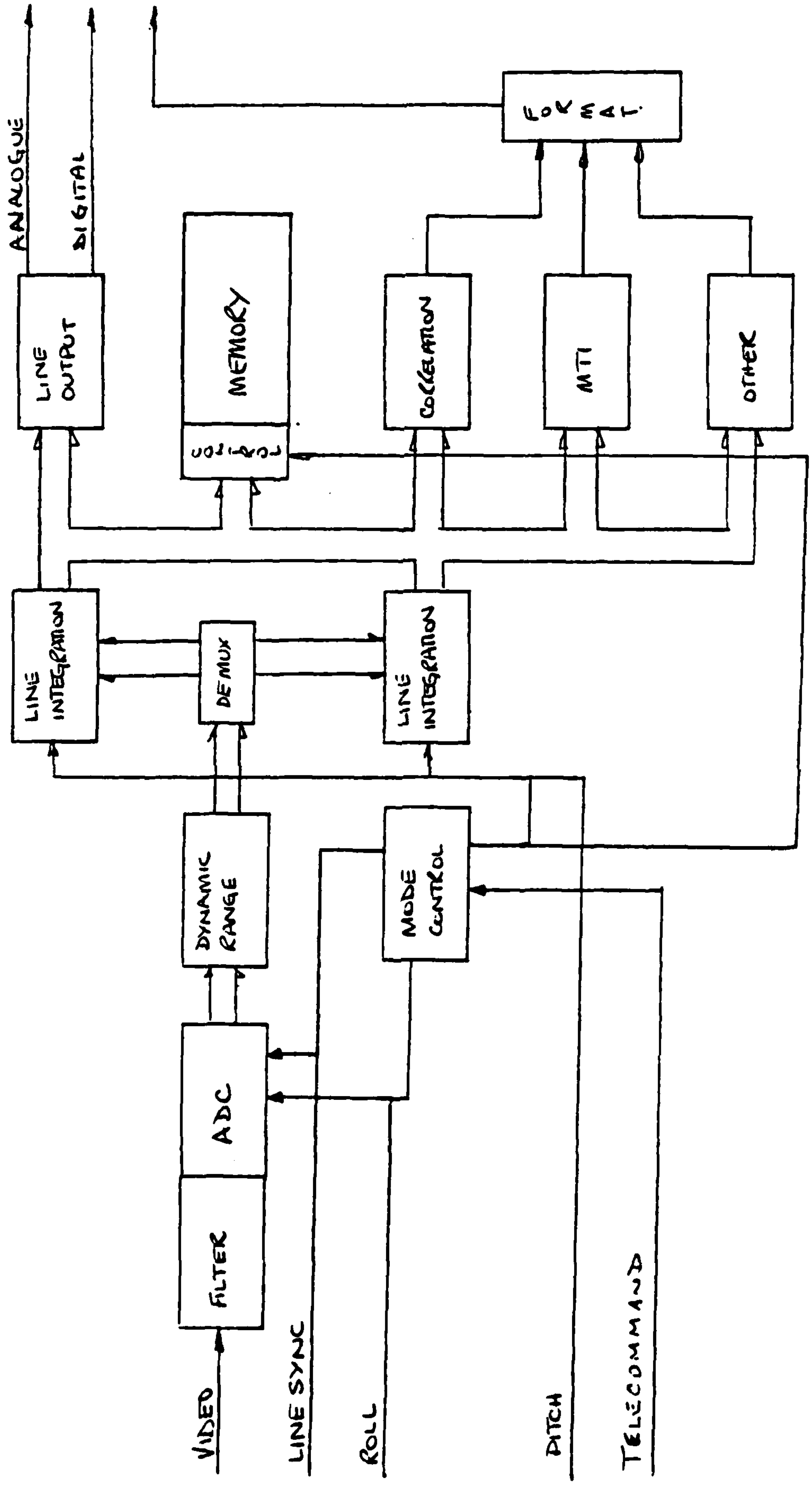

ANALOGUE
DIGITAL
LINE OUTPUT
MEMORY
CORRELATION
MTI
OTHER
LINE INTEGRATION
DE MUX
LINE INTEGRATION
DYNAMIC RANGE
MODE CONTROL
ADC
FILTER
VIDEO
LINE SYNC
ROLL
PITCH
TELECOMMAND

Fig 1

Fig 2

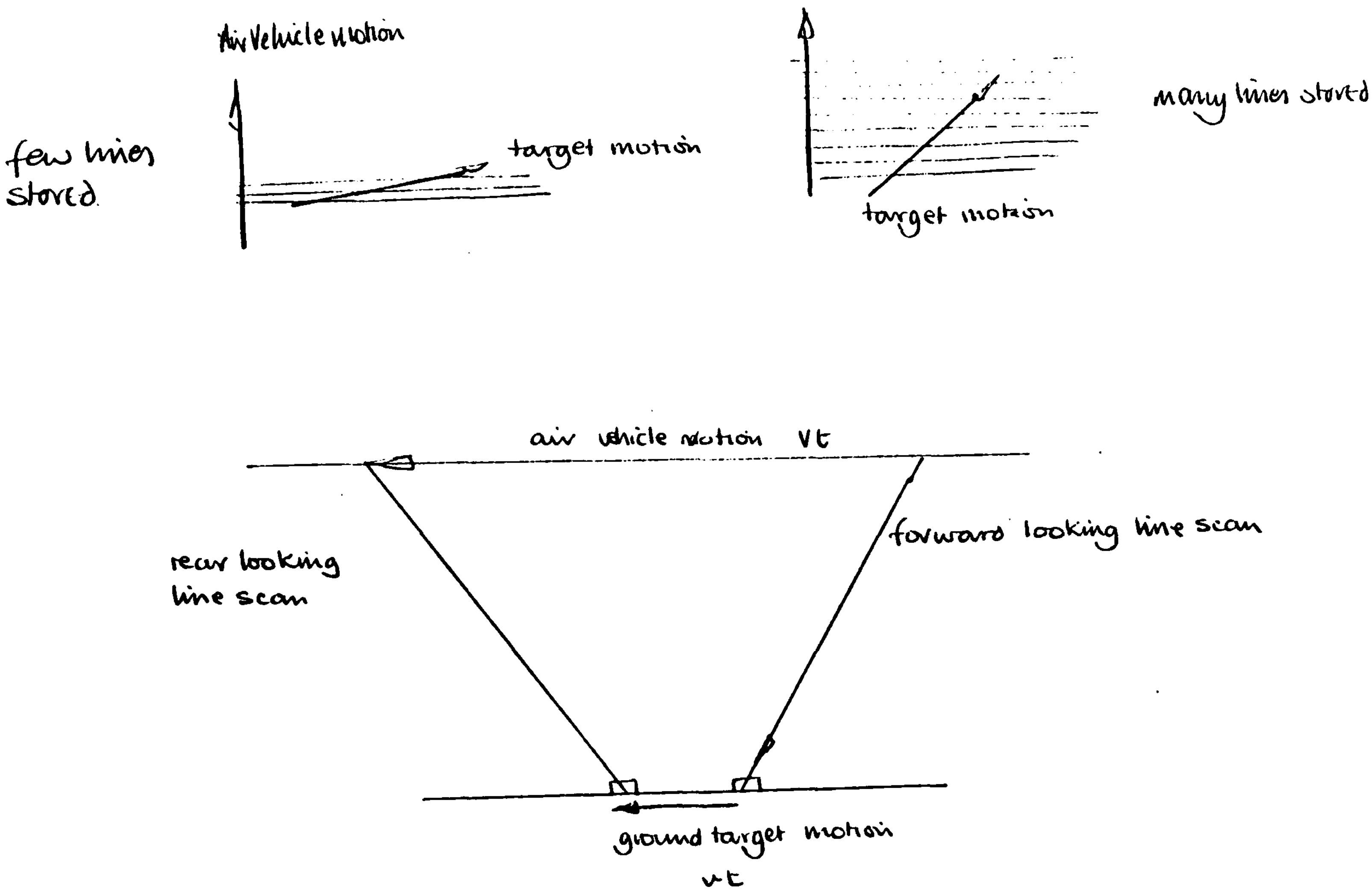
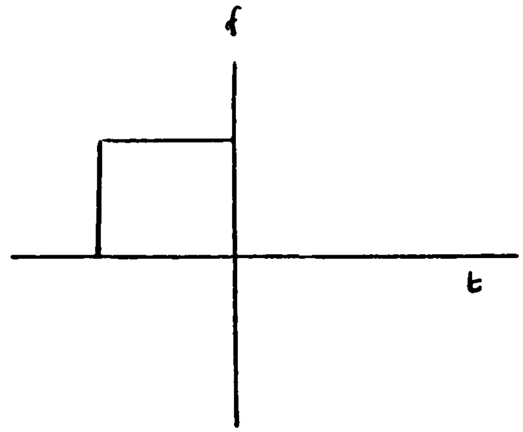
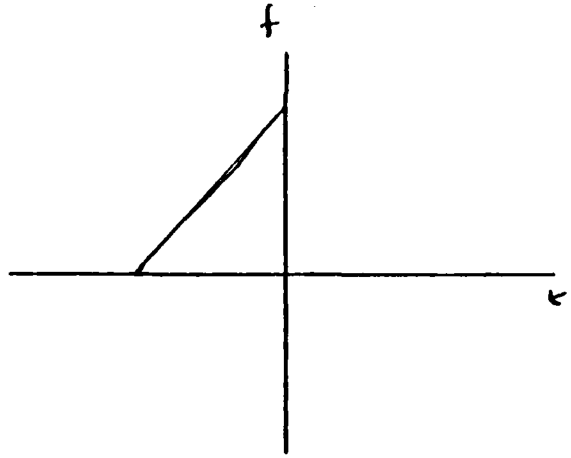

few lines stored
Air Vehicle motion
target motion
target motion
many lines stored
air vehicle motion Vt
rear looking line scan
forward looking line scan
ground target motion
vt

Fig 2



$$A_n = \frac{1}{n} \sum_{i=1}^{i=n} I_i$$

equal weighting function



$$A_n = \frac{A_{n-1} + I_n}{2}$$

saw tooth weighting function

Fig 3 Integration weighting functions

Fig 4

1

$$r = \frac{\overline{XY}}{\sqrt{\overline{X^2}\;\overline{Y^2}}}$$

2.

$$r = \frac{1}{n}\sum_{i=1}^{i=n}(x_i - \bar{x})(y_i - \bar{y})$$

3

$$r = \sum_{i=1}^{i=n} x_i - y_i$$

Fig 4 Correlation algorithms

REPORT DOCUMENTATION PAGE

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